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**14. ABSTRACT**
Immersive VEs (IVEs) have had difficulty simulating large-scale environments because they typically have a limited tracking area. This research study techniques has established that IVEs which incorporate a wearable rendering unit can simulate virtual worlds of unlimited size. The work has overcome the physical space constraints of wearable IVEs by developing and implementing Redirected Walking (RDW). RDW works by imperceptibly rotating the virtual scene around the user's viewpoint so that the user's real body is continually directed away from

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| UU | UU | UU | UU | | Eric Bachmann |
| | | | | | 19b. TELEPHONE NUMBER |
| | | | | | 513-529-0786 |

**Report Title**

Realistic Simulation of Environments of Unlimited Size in
Immersive Virtual Environments - Final Report

## ABSTRACT

Immersive VEs (IVEs) have had difficulty simulating large-scale environments because they typically have a limited tracking area. This research study techniques has established that IVEs which incorporate a wearable rendering unit can simulate virtual worlds of unlimited size. The work has overcome the physical space constraints of wearable IVEs by developing and implementing Redirected Walking (RDW). RDW works by imperceptibly rotating the virtual scene around the user's viewpoint so that the user's real body is continually directed away from the boundaries of the tracking space. Experiments have been
completed which examine the effects of RDW on user performance while involved in both constrained and unconstrained navigation tasks and which compare the
performance of generalized Redirected Walking algorithms. Preliminary work has been completed on Fully Optimized RDW for Constrained Environments(FORCE). Results indicate that the FORCE algorithm performs better than generalized
algorithms and can take advantage of all available space in concave tracking areas. Preliminary work has also show that RDW can be used enable multiple users to simultaneously share a tracking area.

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## Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

### (a) Papers published in peer-reviewed journals (N/A for none)

| Received | | Paper |
|---|---|---|
| 12/26/2012 | 1.00 | Eric Hodgson, Eric Bachmann, David Waller. Redirected walking to explore virtual environments, ACM Transactions on Applied Perception, (11 2011): 0. doi: 10.1145/2043603.2043604 |
| 12/26/2012 | 4.00 | Xiaoping Yun, James Calusdian, Eric R. Bachmann, Robert B. McGhee. Estimation of Human Foot Motion During Normal Walking Using Inertial and Magnetic Sensor Measurements, IEEE Transactions on Instrumentation and Measurement, (07 2012): 0. doi: 10.1109/TIM.2011.2179830 |

**TOTAL:** 2

**Number of Papers published in peer-reviewed journals:**

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### (b) Papers published in non-peer-reviewed journals (N/A for none)

| Received | Paper |
|---|---|

**TOTAL:**

**Number of Papers published in non peer-reviewed journals:**

## (c) Presentations

**Number of Presentations:** 0.00

## Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

| Received | Paper |
|---|---|

**TOTAL:**

**Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

## Peer-Reviewed Conference Proceeding publications (other than abstracts):

| Received | | Paper |
|---|---|---|
| 01/02/2013 | 13.00 | Eric R. Bachmann, Jeannette Holm, Michael A. Zmuda, Eric Hodgson. Collision Prediction and Prevention in a Simultaneous Two-User Immersive Virtual Environment, IEEE VR 2013. 2013/03/16 00:00:00, . : , |
| 01/02/2013 | 14.00 | Michael Zmuda, Eric Bachmann, Eric Hodgson, Joshua Wonser. Improved Resetting in Virtual Environments , IEEE VR 2014. 2013/03/16 00:00:00, . : , |
| 12/26/2012 | 5.00 | James Calusdian, Eric Hodgson, Xiaoping Yun, Eric Bachmann. In situ heading drift correction for human position tracking using foot-mounted inertial/magnetic sensors, 2012 IEEE International Conference on Robotics and Automation (ICRA). 2012/05/14 00:00:00, St Paul, MN, USA. : , |
| 12/26/2012 | 3.00 | Eric R. Bachmann, Michael Zmuda, James Calusdian, Xiaoping Yun, Eric Hodgson, David Waller. Going anywhere anywhere: Creating a low cost portable immersive VE system, 2012 17th International Conference on Computer Games: AI, Animation, Mobile, Interactive Multimedia, Educational & Serious Games (CGAMES). 2012/07/30 00:00:00, Louisville, KY, USA. : , |
| 12/27/2012 | 12.00 | James Calusdian, Xiaoping Yun, Eric Bachmann. Adaptive-gain complementary filter of inertial and magnetic data for orientation estimation, 2011 IEEE International Conference on Robotics and Automation (ICRA). 2011/05/09 00:00:00, Shanghai, China. : , |

**TOTAL:** **5**

**Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):**

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## (d) Manuscripts

| Received | | Paper |
|---|---|---|
| 12/27/2012 | 9.00 | Michael Zmuda, Joshua L. Wonser, Eric R. Bachmann, Eric Hodgson. Optimizing Constrained-Environment Redirected Walking Instructions Using Search Techniques, IEEE Transactions on Visualization and Computer Graphics (12 2012) |
| 12/27/2012 | 10.00 | Eric Hodgson, Eric R. Bachmann. Comparing Four Approaches to Generalized RedirectedWalking: Simulation and Live User Data, IEEE TRANSACTIONS ON COMPUTER VISUALIZATION AND COMPUTER GRAPHICS (12 2012) |
| 12/27/2012 | 11.00 | Eric Hodgson, Eric R. Bachmann, David Vincent, Michael Zmuda, James Calusdian. Portable Wearable Immersive VE Simulation System – A Discussion and Demonstration, Presence (01 2013) |

**TOTAL:** **3**

**Number of Manuscripts:**

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## Books

| Received | | Paper |
|---|---|---|
| 01/02/2013 | 8.00 | David Waller, Eric Hodgson. Sensory contributions to spatial knowledge of real and virtual environments, Human Walking in Virtual Environments: Perception, Technology, and Applications: Springer, (06 2013) |

**TOTAL:** **1**

## Patents Submitted

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## Patents Awarded

United States Patent: Method for the Determination of Three-dimension Body Attitude Using the Adaptive-Gain complementary Filter, 2012.

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## Awards

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## Graduate Students

| NAME | PERCENT_SUPPORTED | Discipline |
|---|---|---|
| Jeannette Holm | 0.50 | |
| David Vincent | 0.37 | |
| Joshua Wonser | 0.50 | |
| Tyler Thrash | 0.10 | |
| Debadrita Sarkar | 0.00 | |
| **FTE Equivalent:** | **1.47** | |
| **Total Number:** | **5** | |

## Names of Post Doctorates

| NAME | PERCENT_SUPPORTED |
|---|---|
| Eric Hodgson | 0.35 |
| Pete Simko | 0.30 |
| **FTE Equivalent:** | **0.65** |
| **Total Number:** | **2** |

## Names of Faculty Supported

| NAME | PERCENT_SUPPORTED | National Academy Member |
|---|---|---|
| Eric Bachmann | 0.20 | |
| Davic Waller | 0.08 | |
| **FTE Equivalent:** | **0.28** | |
| **Total Number:** | **2** | |

## Names of Under Graduate students supported

| NAME | PERCENT_SUPPORTED | Discipline |
|---|---|---|
| Andrew Bair | 0.05 | Computer and Computational Sciences |
| Fred Coulson | 0.20 | Computer and Computational Sciences |
| Andrew Oberlin | 0.10 | Computer and Computational Sciences |
| Kara Rosine | 0.00 | Computer and Computational Sciences |
| Joshua Wonser | 0.00 | Computer and Computational Sciences |
| William Morrison | 0.00 | Computer and Computational Sciences |
| Michael Jacobs | 0.00 | Computer and Computational Sciences |
| Hana Berns | 0.00 | Cognitive, Neural, and Behavioral Sciences |
| Zachary Hathaway | 0.00 | Biosciences |
| Hung Nguyen | 0.00 | Computer and Computational Sciences |
| Jeffrey Raig | 0.00 | Computer and Computational Sciences |
| Youxuan Jiang | 0.00 | Computer and Computational Sciences |
| **FTE Equivalent:** | **0.35** | |
| **Total Number:** | **12** | |

## Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

| | |
|---|---|
| The number of undergraduates funded by this agreement who graduated during this period: ...... | 1.00 |
| The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... | 1.00 |
| The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... | 0.00 |
| Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... | 0.00 |
| Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... | 0.00 |
| The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ...... | 0.00 |
| The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... | 0.00 |

## Names of Personnel receiving masters degrees

NAME
Jeannette Holm
David Vincent

**Total Number:** **2**

## Names of personnel receiving PHDs

NAME

**Total Number:**

## Names of other research staff

NAME PERCENT_SUPPORTED

**FTE Equivalent:**
**Total Number:**

## Sub Contractors (DD882)

## Inventions (DD882)

## Scientific Progress

See Attachment

## Technology Transfer

**Portable Wearable Immersive Virtual Environment Systems**

Virtual environments (VE) have become an invaluable tool for research, development, training, healthcare, commerce, communication, and education, as well as a medium for entertainment. Immersive virtual environments (IVE) which incorporate a wearable rendering system and a head mounted display (HMD) allow users to explore simulated environments by naturally walking, turning, and looking (Fig 1.). Such natural navigation and the associated multisensory stimulation have been shown to provide a greater sense of realism to users (Ruddle et al. 2011, Usoh et al. 1999, Slater et al. 1995a). Indeed, one of the strengths of VEs is the ability to present multi-modal sensory information to users to holistically simulate the experience of being present or immersed in the synthetic, virtual reality. Rather than merely presenting optic flow, compelling visual information is augmented with some combination of positional auditory cues, proprioceptive, kinesthetic, and inertial feedback about one's movement.

Fig 1. Portable wearable IVE system in an outdoor environment.

With support from the Army Research Office (ARO) and the National Science Foundation (NSF), the PIs have spent the last several years developing wearable IVE systems, using backpack-mounted rendering computers, HMDs, and body-worn motion sensors. This research can be separated into two major areas of focus. This first is the study redirected walking (RDW) techniques (funded primarily by ARO). By imperceptibly rotating the virtual world about the user, RDW makes it possible for immersed users to avoid tracking area boundaries while exploring virtual worlds which can be unlimited in extent. The second area of focus involves portable position tracking systems. The goal of this work is to produce systems with require little or no setup prior to and can be used in and moved to any location. Through this research, systems which are capable of providing both the smooth high frequency position updates necessary to an effective locomotion interface and the absolute position necessary for RDW and obstacle avoidance have been created. To date the research has spawned one book chapter (Waller & Hodgson 2013), seven peer-reviewed publications (Bachmann et al. 2012a; Zmuda et al. 2012; Hodgson & Bachmann 2013; Hodgson et al. 2011; Yun et al. 2012; Bachmann et al. 2012b; Yun et al. 2011), three invited talks, and an additional six manuscripts that are currently in preparation or under peer review. The funding has also resulted in the creation of 1 1/2 full time jobs, has provided financial support for five graduate students and one postdoctoral fellow, and has spawned talks with seven regional, national, and international industry partners about commercialization opportunities or applications of the hardware and software developed under this grant. Finally, the PIs are in talks with a local high school about taking the portable IVE system to their gym to exhibit to students and support a curricular project.

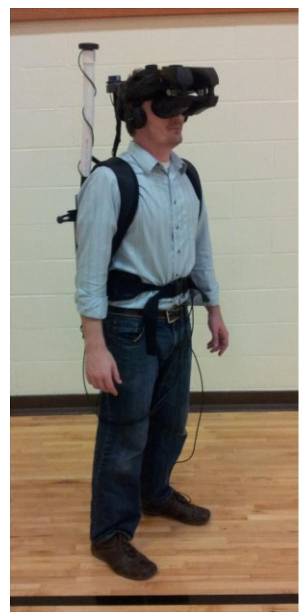

Fig. 2. Portable wearable IVE system in use in an indoor environment.

Unlike traditional HMD-based systems, users of portable IVE systems which incorporate a wearable rendering systems are completely untethered and can roam freely over a wide area. Proprioceptive, vestibular, and efferent sensory information for virtual walking in a forward, sideways, or backward direction or potentially running are nearly perfect, because users are in fact actually moving naturally in the physical world. The latest iteration of this system is free of any fixed infrastructure and can easily be used in any large open area such as a parking lot, field, hanger, gymnasium, or conceivably even a remote desert. It is the opinion of PIs' that using natural walking as the locomotion interface provides the best and most veridical sensory information to users as they move, and is the most intuitive and user-friendly method of navigation – no training is ever required.

Historically, the tradeoff of such a natural interface was that the range of user motion was severely limited. If one had a 10m x 10m lab, for example, a user could not safely walk more than 4m from the lab's center.  However, recent advances by the PIs' and others (described below) have made it possible to overcome this using a technique known as Redirected Walking (Razzaque 2005), and to enable users to walk naturally through VE's of unlimited extent. Likewise the development of portable position tracking technologies which require no infrastructure and little setup has made it possible to transport such a system in the trunk of a small car to much larger, ad-hoc tracking areas.

Figures 1 and 2 depict 3rd-generation wearable IVE systems built by the PIs. Common components in both systems include a HMD to which an inertial/magnetic orientation has been attached, a backpack mounted laptop used as a wearable rendering unit, and a backpack mounted video control unit and battery pack. In both figures, foot mounted inertial/magnetic sensors modules are attached to the feet for the purpose of infrastructure free position tracking. In the outdoor configuration depicted in Fig. 1, absolute position fixes are obtained on a periodic basis using the mast mounted GPS antennae. Fig. 2 depicts a system use in an indoor environment. Again foot mounted inertial/magnetic sensor modules are used to obtain smooth high frequency position updates. Absolutes position fixes used for drift correction are obtained from an ultrasonic TDOA (time difference of arrival) system. More recent work by the principle investigators has indicated that both the TDOA sensors and the foot mounted could be replaced by a stationary or backpack mounted scanning laser range finder.

*Redirected Walking*

With traditional immersive VE systems, the scale of a virtual simulation is typically limited to the size of the tracking area. RDW, a technique first examined by Razzaque (2005), overcomes the physical limitations of a tracking area by imperceptibly rotating the virtual scene about the user and by amplifying or dilating the user's motions – including both turning and walking. These adjustments systematically guide the user on a curved path within the real world while the user perceives that they are following a straight line in the VE. Appropriate application of these injected rotations can gradually direct users away from real-world obstacles and back into open, navigable space. If the rate of rotation introduced by RDW is small enough, it is not perceived by the user and he or she will subconsciously respond by turning in the real world in order to maintain the desired heading in the VE.

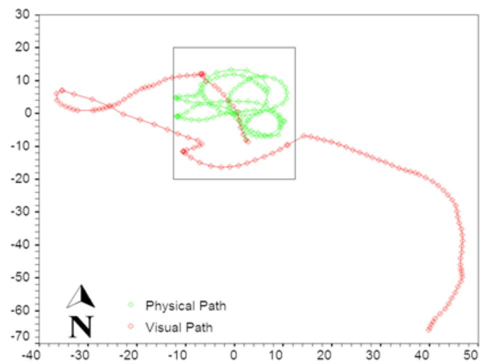

Fig. 3. Typical visual and physical paths for a user being redirected in a VE. Small rectangle represents the physical tracking area. Units are in meters.

In (Hodgson, Bachmann and Waller 2011), the PIs implemented a real-time generalized RDW algorithm and demonstrated its use with live users for the first time (i.e., not merely a computer simulation). This work included experiments during which users navigated through a very large virtual forest and completing a shopping search task in a full-scale virtual grocery store. During the course of these experiments, users almost always traveled virtual distances which would have placed them well outside the physical tracking area (Fig 3.). In spatial memory tasks, data showed no detriment to using the subtle sensorimotor distortions necessary for RDW to work. Post-experiment surveys indicated that RDW went relatively unnoticed and did not induce simulator sickness. In more recent work (Hodgson and Bachmann 2013), the PIs conducted a systematic comparison of the performance of several alternative generalized RDW walking algorithms and to establish how minimum sized tracking area required for RDW algorithms of different type. The work involved both live user studies and simulations. Users, on average, were able to travel to a maximum visual distance of 55.65m ± 0.82 from the laboratory's center, despite starting within 22.5m of the furthest lab wall.  The work established that with present methods RDW could be carried out imperceptible in a tracking area with a radius of 17m (Fig. 4).

As part of the previous NSF grant to develop RDW techniques, the PIs have recently studied the use of RDW algorithms in constrained environments. A grocery store (Fig. 5) with rigid aisles, for example, limits a user's future actions to a small set of predictable options and makes it possible to predict a her or his likely direction and distance of travel.  This can allow RDW to utilize otherwise undesirable space by, for example, safely steering a user along a rightward wall when it is known that a particular portion of the VE does not permit rightward turns.  This technique is dubbed Fully Optimized RDW for Constrained Environments (FORCE; Zmuda et al. 2013), and has compared favorably to established generalized RDW methods in simulation. In failure cases where generalized RDW do not prevent a user from leaving the tracking space, FORCE succeeds nearly 95% of the time.

Finally, the PIs have demonstrated that RDW can safely steer multiple users away from each other when there are several immersed users within the same tracking area (Holm 2012). Work is underway to apply multi-user collision prediction and avoidance algorithms to live user navigation in a VE.

While these latter studies are unrelated to the simulation of slope, they serve to illustrate diligence in pursuing the previous objectives that were funded by the NSF, and a track record of successfully applying RDW techniques to enhance the safety, utility, and effectiveness of natural walking locomotion interfaces in IVE.

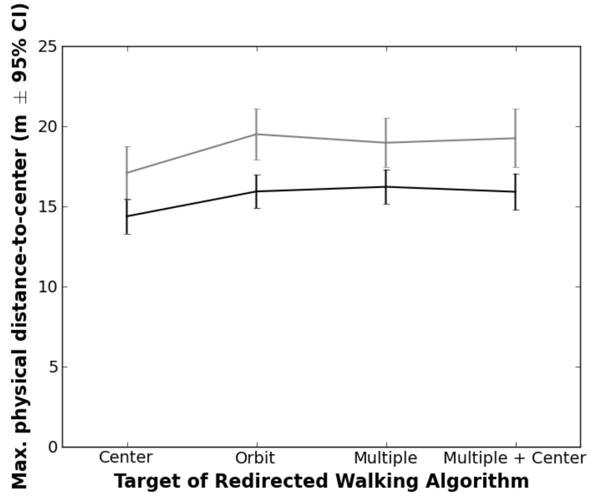


Fig. 4: Maximum physical distance of simulated users with each algorithm. The darker line shows the results when using a 7.5m turn radius; the lighter line shows a 22m turn radius.

Fig. 5. Predicted path of a user in a constrained VE. Such predictions can optimize redirection.

*Portable Position Tracking*

Ongoing work by the PIs has resulted in the development of a Self-Contained Inertial Position Tracking (SCIPT) designed to serve as a locomotion interface for portable immersive VE systems (Yun et al. 2011). It can produce smooth high frequency updates with drift error of less than 1% of total distance traveled in outdoor applications, with occasional GPS fixes correcting the remaining drift. SCIPT is based on the use of foot mounted miniature inertial/magnetic measurement units and zero velocity updating, which takes advantage of the fact that walking, side stepping, and running include repeated recognizable periods during which the foot is on the ground and has a known velocity and acceleration of zero. These periods allow us to determine and remove the sensor drift error that occurs during each step to accurately calculate the direction and magnitude of movement. Nearly all error in SCIPT position estimates is due to heading errors caused magnetic anomalies. The PIs are currently collaborating with the PNI Corporation of Santa Rosa, CA and have incorporated their SpacePoint 9-axis inertial/magnetic sensor module into the SCIPT system. The SpacePoint utilizes a novel fusion algorithm that produces superior estimations of azimuth in the presence of magnetic anomalies. It is anticipated that this collaboration will produce highly accurate sourceless position estimates in both indoor and outdoor environments.

In demonstrating this system in conjunction with RDW, a series of long walks, up to 2km in length, were conducted along a virtual straight path. As shown in Fig.6, no tracking drift was apparent over these large distances and users were easily contained in the outdoor field selected as a tracking space. For indoor applications where GPS is unavailable, work by the PIs has resulted in the creation of an entirely new position tracking system capable of providing absolute position estimates at update rates similar GPS. The system uses TDOA and a novel Multi-Dimensional Scaling (MDS) algorithm to resolve the positions of all users in a common tracking area (Vincent, 2012). The algorithm takes ultrasonic range measurements amongst multiple users and a series of arbitrarily-placed base stations, and uses SCIPT displacement vectors to provide updates between ultrasonic sensor readings. The range measurements provide internode distances between each immersed user and between users and base nodes, which can be resolved to reveal the global configuration of users along with their absolute positions. If within range of at least one other node in the system, SCIPT drift correction can still be accomplished by this method. Thus, the system can operate robustly over a relatively large area. While indoors, or when using RDW, users should rarely exceed this distance.

The PIs in collaboration with researchers at the Naval Postgraduate School in Monterey, CA. have also developed a system of locating users by means of a laser range scanner. The precision, range, and resolution of low cost scanning laser range finders makes it possible to perform Simultaneous Location and Mapping (SLAM) to both generate a map of an ad-hoc, indoor tracking area and to locate users within that map. Generating a room map has the added benefit of providing physical limit information to RDW algorithms, so that extra failsafe methods can be employed to keep users from colliding with obstacles. Multiple users can be tracked effectively with a single, tripod-mounted laser at the side of a room. Alternatively, the laser can easily be mounted to the PIs' backpack rendering system in an outward-facing configuration for indoor or outdoor use.

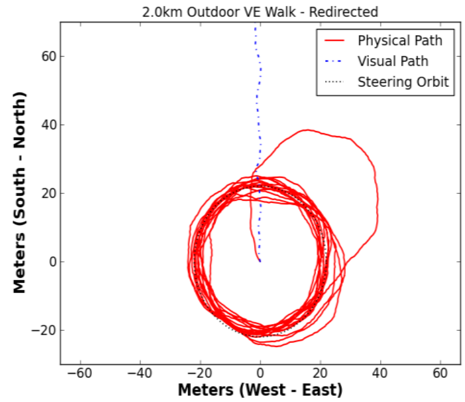


Fig. 6. Plot of a 2 km (1.24 mi) virtual straight walk

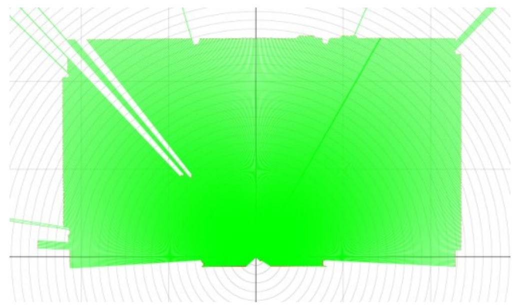

Fig. 7. Laser ranging scan of 25m x 44m HIVE. Unit is positioned in the center of the wall at the bottom of the plot. Shorter returns indicate the position of two users on the left.

Again, these prior research efforts are somewhat tangential to the present objective of simulating slope. However, we hope to illustrate the depth and experience that the PIs have in developing locomotion interfaces in general, and in tracking foot motion and stepping patterns specifically. The SCIPT system that we have developed is extremely well suited to measuring the physical effort that users may exert when trying to navigate up a virtual hill. Variations in the acceleration or angle of one's foot can be evaluated when determining the corresponding vertical and horizontal displacement in the virtual world. While scaling effort is easily possible with other systems – including treadmills and even desktop VEs – we believe that SCIPT will offer the highest-fidelity experience for end users.

*Significance*

To date, most VR facilities have been centralized, specialized, and expensive, and have thus been relatively unavailable to a great majority of the population. In creating VR systems that are portable and relatively inexpensive, this research represents a significant step toward making VR less exclusive. De-centralizing VR will make the technology available to a much broader range of people than has heretofore been possible, providing first-hand exposure to cutting-edge concepts and models in science and technology to any population that educators or researchers chose.

In addition to representing a qualitative change in how VR has heretofore been generally conceptualized, the proposed research delivers significant enhancements to the component technologies that comprise it. For example, while the commercial XSENS MVN system (Xsens Technologies B.V., 2009) is capable of providing full body motion capture and position tracking without a supporting infrastructure it is relatively expensive, and requires users to wear complex equipment, and cannot be easily-integrated into current VR systems that simulate large-scale spaces. The ExpeditionDI system (Quantum3D) currently in use by the US military is portable and allows multiple users to participate simultaneously in a virtual simulation, but does not provide users with realistic proprioceptive and vestibular cues. Similarly, the proposed development of redirected walking in large physical spaces successfully enables users to explore extremely large simulated spaces in a manner that is much more realistic than that provided by current navigational interfaces such as the omnidirectional treadmill.

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Bachmann, E. R., Calusdian, J., Hodgson, E., Yun, X. (2012). In-situ heading drift correction for human position tracking using foot-mounted inertial/magnetic sensors. *Proceedings of the IEEE International Conference on Robotics and Automation, ICRA 2012, St. Paul, Minnesota, USA.*

*Hodgson, E., & Bachmann, E.R, (2013, conditionally accepted). Comparing Four Approaches to Generalized Redirected Walking: Simulation and Live User Data. IEEE Transactions on Computer Visualization and Computer Graphics.*

Hodgson, E., Bachmann, E. R., & Waller, D. (2011). Steering Immersed Users of Virtual Environments: Assessing the Potential for Spatial Interference. *ACM Transactions on Applied Perception, 8*(4). Hodgson, E., Bachmann, E. R. (In Review). Comparing Four Approaches to Generalized Redirected Walking: Simulation and Live User Data. *Conditional acceptance IEEE Transactions on Computer Visualization and Computer Graphics*, November 2012.

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Yun, X., Calusdian, J., & Bachmann, E. R. (2011). Adaptive-Gain Complementary Filter of Inertial and Magnetic Data for Orientation Estimation. *Proceedings of the IEEE International Conference on Robotics and Automation*, *ICRA 2011, Shanghai, China, May 2011*.

Zmuda, M., Wonser, J. L., Bachmann, E. R., & Hodgson E., *(2013, conditionally accepted)*. Optimizing Constrained-Environment Redirected Walking Instructions Using Search Techniques. *Conditionally accepted IEEE Transactions on Computer Visualization and Computer Graphics.*